Elimination of Heterodyne Interferometer Nonlinearity by Carrier Phase Modulation

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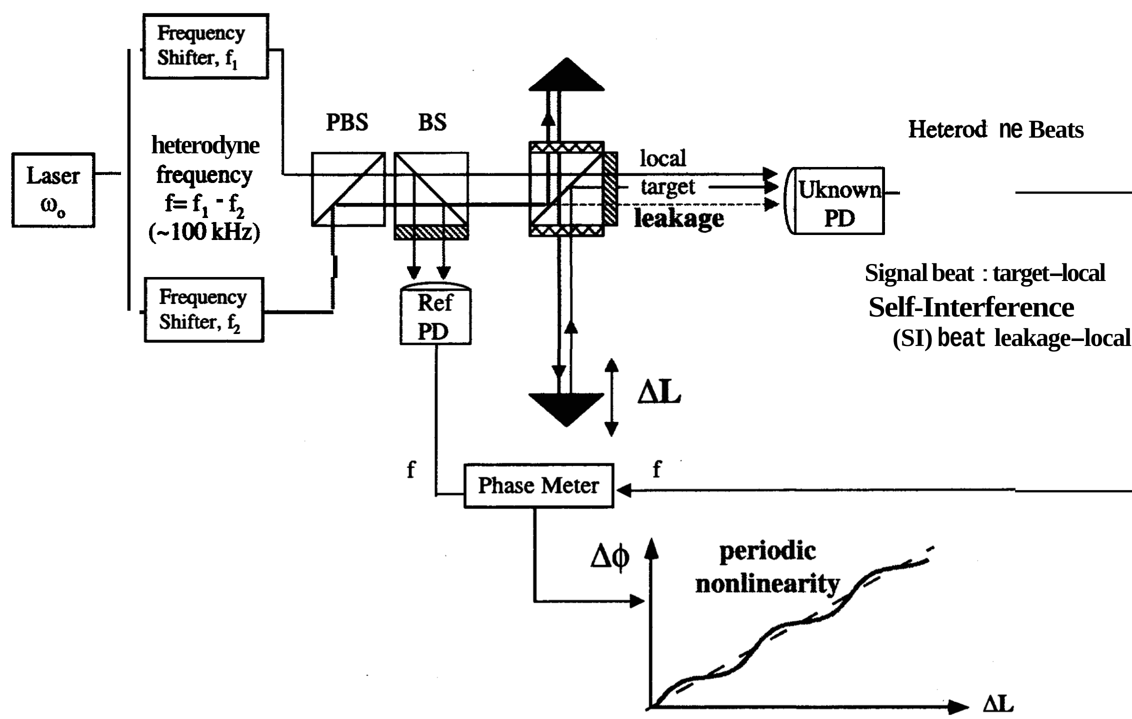
To be presented by Peter Halverson at the
National Research Laboratory of Metrology
Tsukuba, Japan
April 3,2001

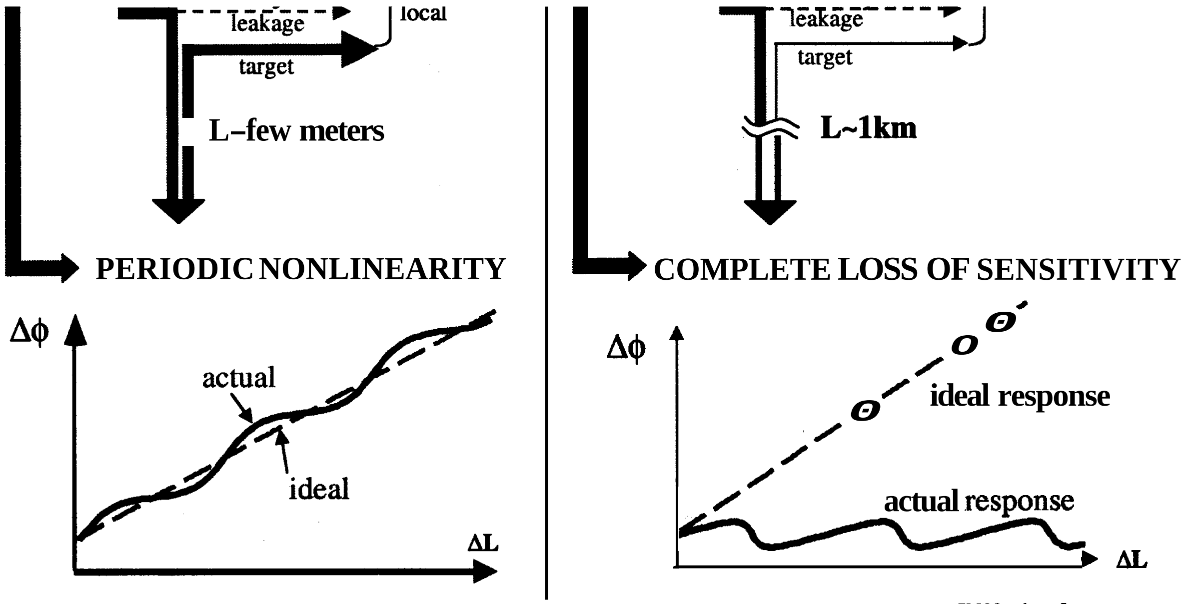
Motivation **and** Outline

- Motivation
  - JPL's Space Technology **3** (ST3) mission requires inter-spacecraft linear metrology:
    - Performance: **11** nanometers at 1 kilometer
    - Implementation: heterodyne interferometer laser gauge
  - Problem:
    - Cyclic Nonlinearity due to Polarization Leakage in heterodyne interferometers
    - **ST3** operating conditions are such that existing methods **of** cyclic nonlinearity suppression could not be used
  - Solution
    - Novel method: Heterodyne Interferometer with Carrier Phase Modulation
- Outline
  - Concept
  - Proof-of-concept experiments
  - Analysis of operation **and** limitations

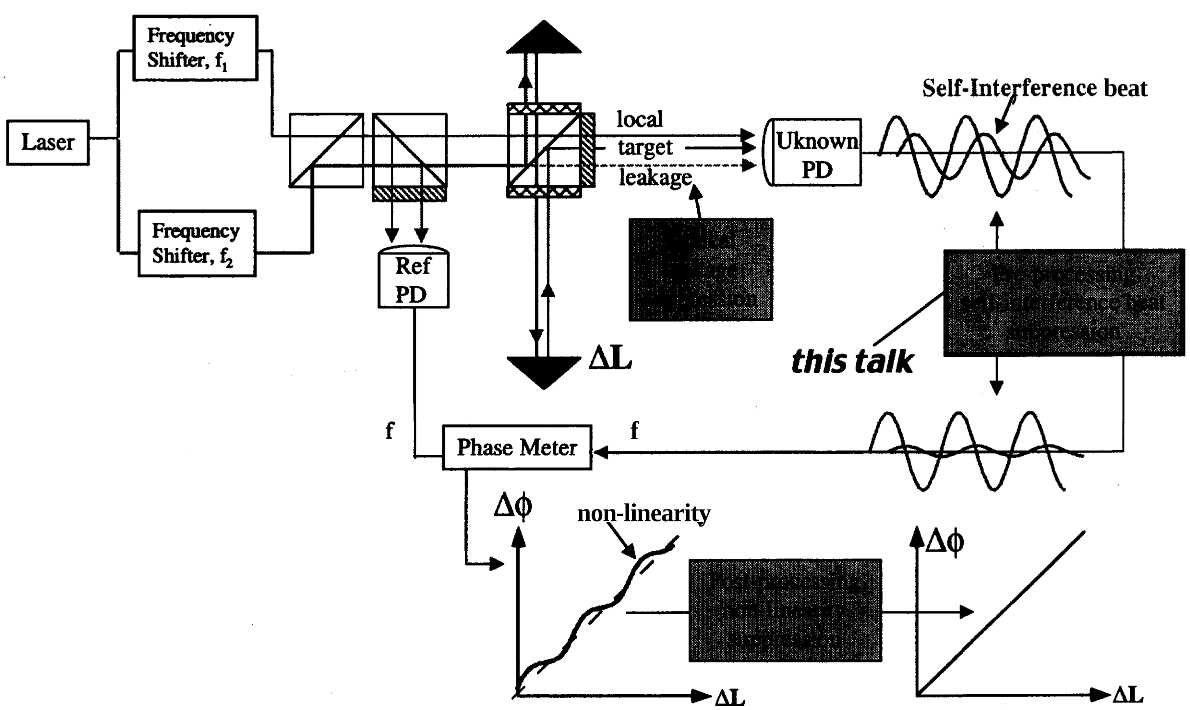
ΔL

JPL Heterodyne Interferometer: Leakage Effects



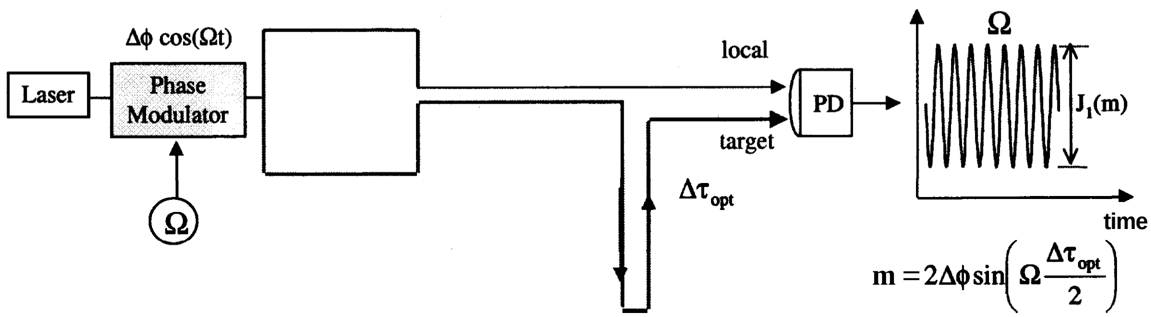


JPL Methods **for** Suppression **of** Leakage **Effects**

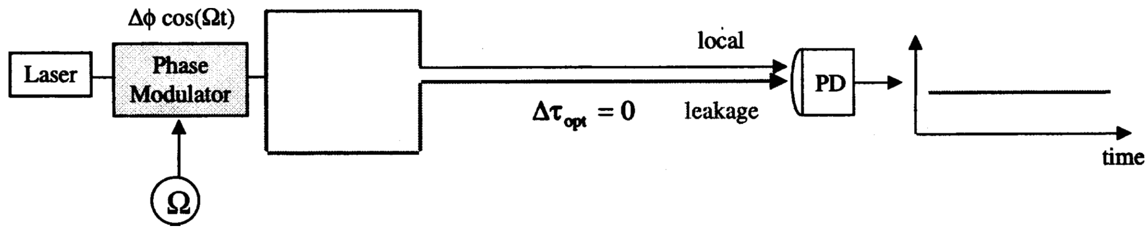


How to Isolate Target Beam Effects from Leakage Beam Effects

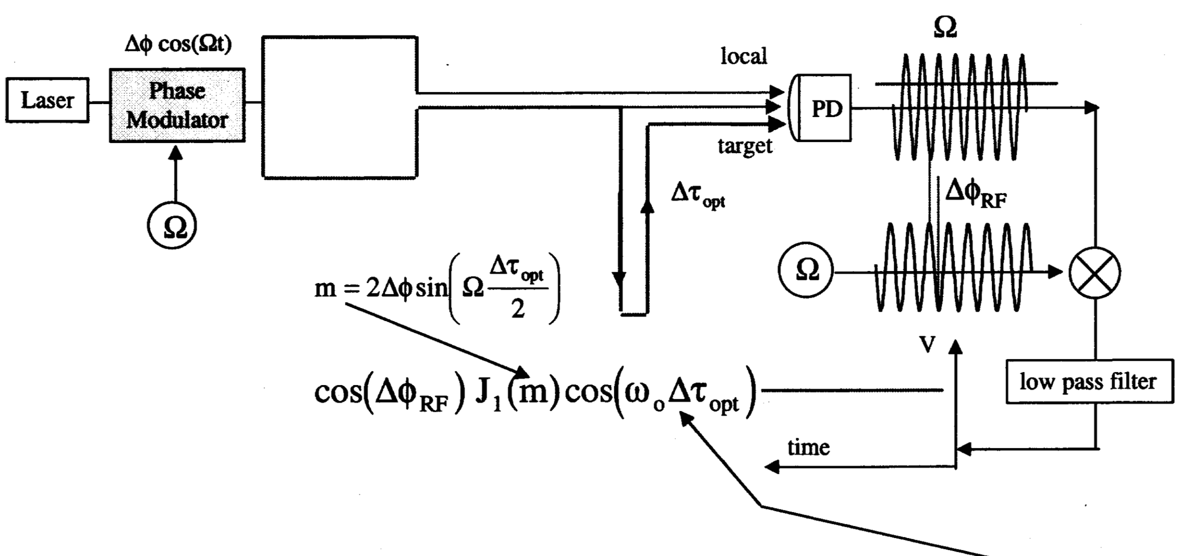
Target Beam sees Time Delay: Phase Modulation -> Intensity Modulation



Leakage Beam sees NO Time Delay: Phase Modulation -> NO Intensity Modulation

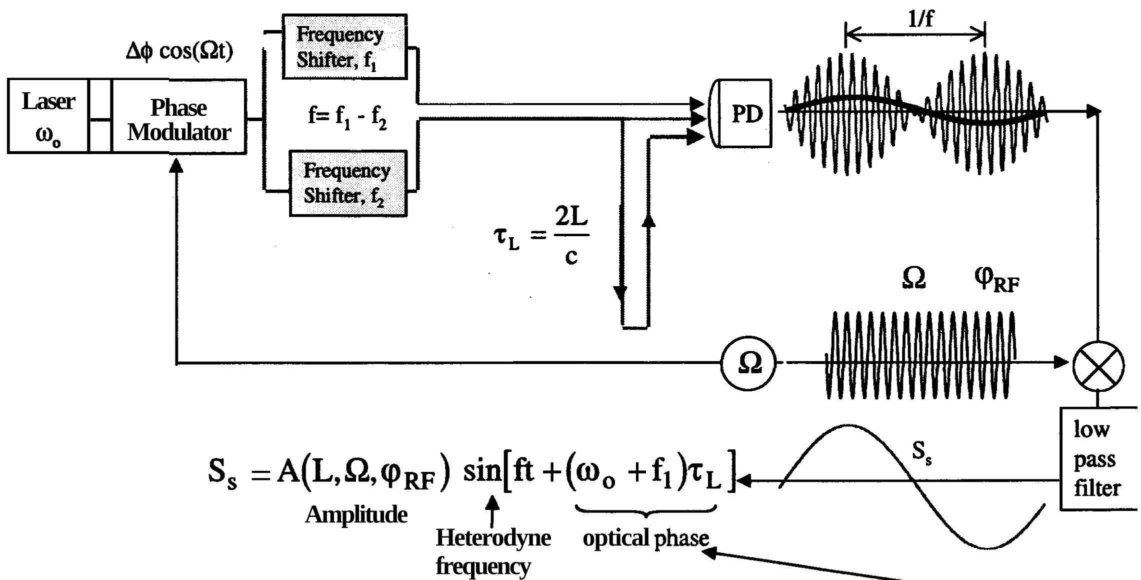


Homodyne Interferometer with Phase Modulation



- **Demodulation at Ω isolates signal from self-interference, but desired optical phase appears in voltage magnitude (not phase)**

JPL Heterodyne Interferometer + Phase Modulation

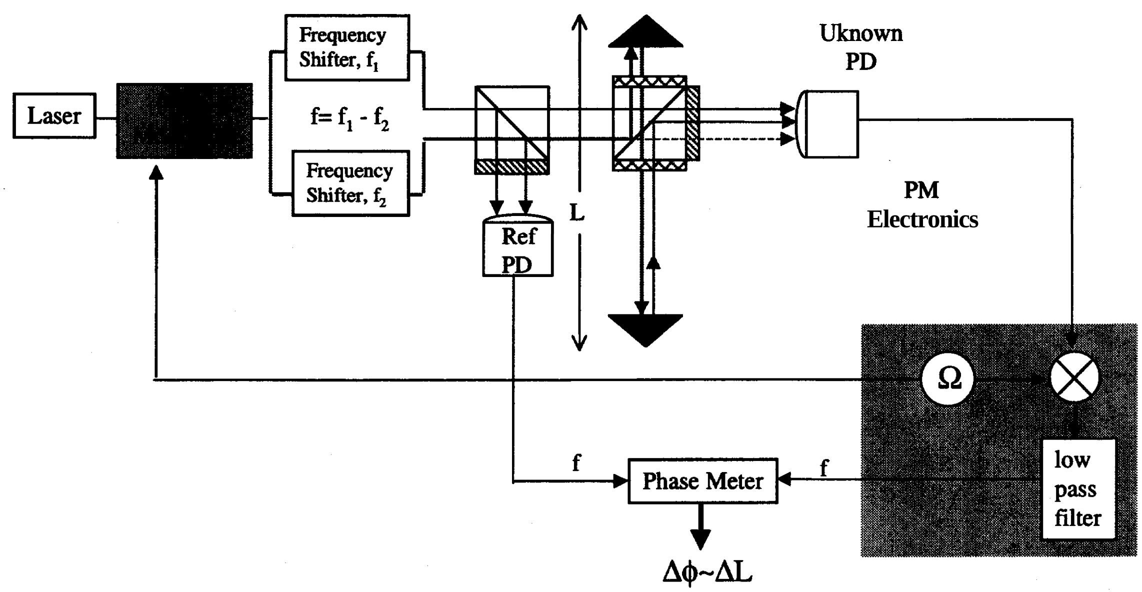


$$S_s = \underbrace{A(L,\Omega,\varphi_{RF})}_{\text{Amplitude}} \sin[\underset{\uparrow}{f}t + \underbrace{(\omega_o + f_1)\tau_L}_{\text{optical phase}}]$$

Heterodyne frequency

- **Demodulation at Ω isolates signal from self-interference, AND desired optical phase appears as phase of the heterodyne beat**

JPL Heterodyne Interferometer with a Phase Modulated Source



- **Heterodyne Interferometer Operation**
- **Self-Interference is suppressed**

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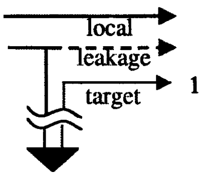
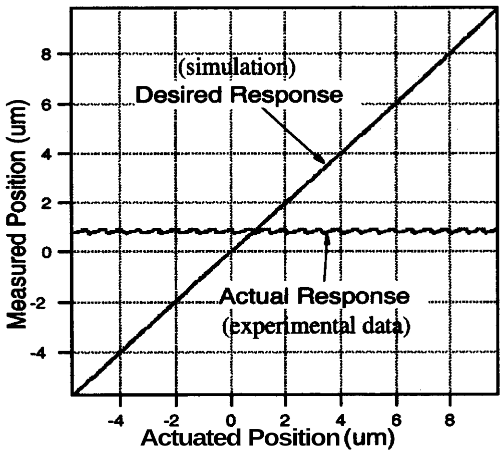
Proof of Concept Experiment



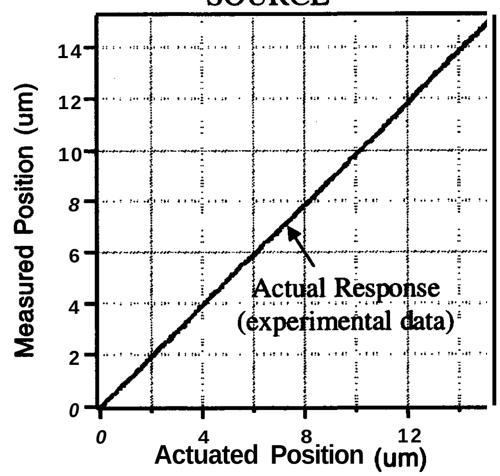
Leakage Intensity twice the Target beam intensity

HETERODYNE INTERFEROMETER



COMPLETE LOSS OF SENSITIVITY

HETERODYNE INTERFEROMETER WITH A PHASE MODULATED SOURCE



SENSITIVITY RECOVERED

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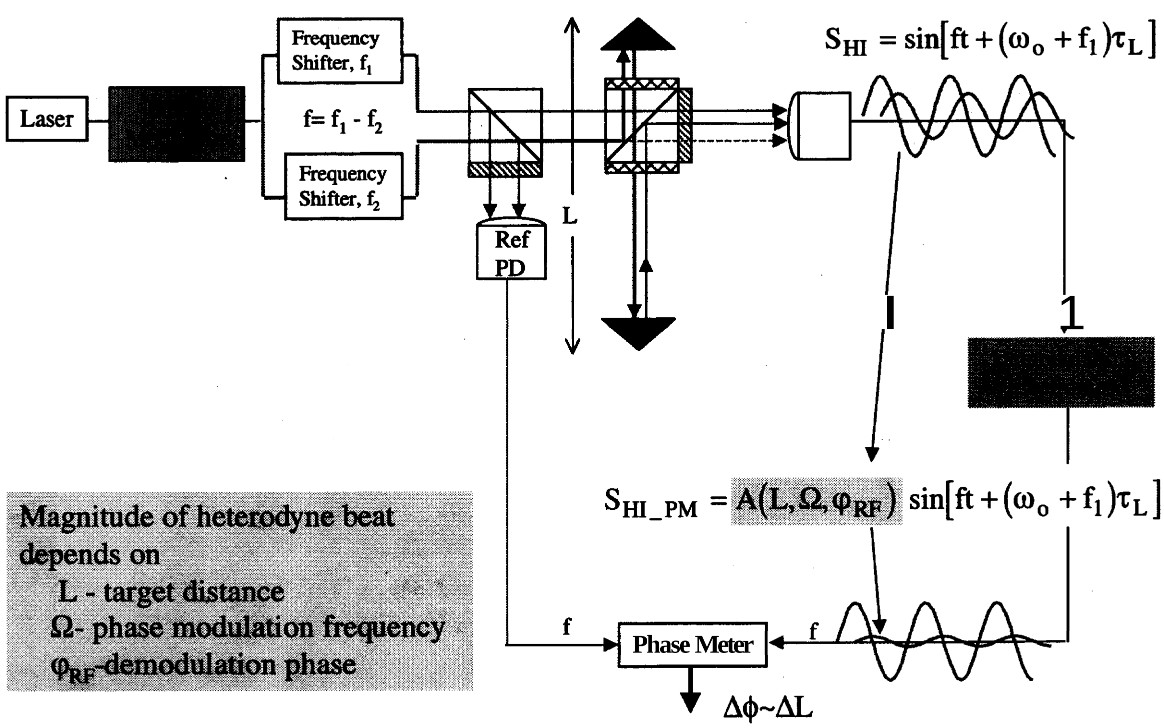
HI-PM: Pre-processing SI suppression



Magnitude of heterodyne beat depends on

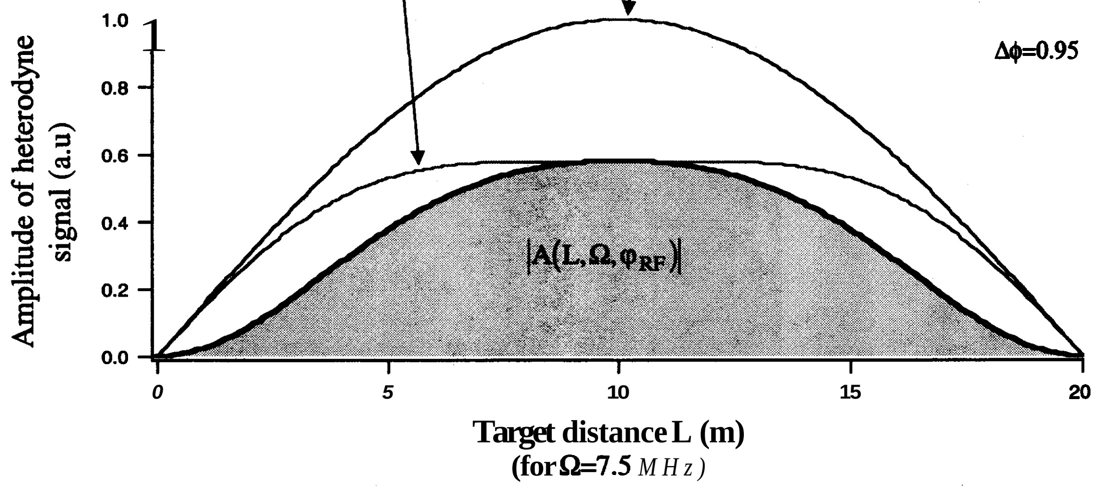
- L - target distance
- Ω- phase modulation frequency
- φ_{RF}-demodulation phase

Amplitude Response

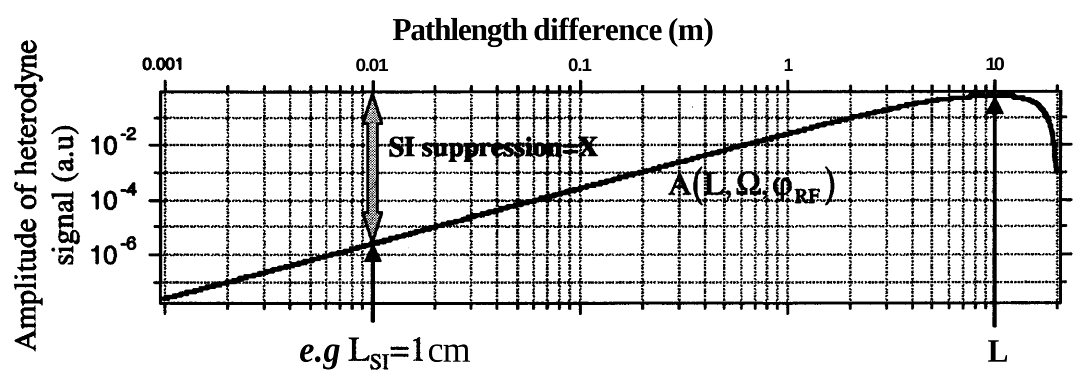
$$S_s = A(L,\Omega,\varphi_{RF})\ \sin[ft + (\omega_o + f_1)\tau_L]$$

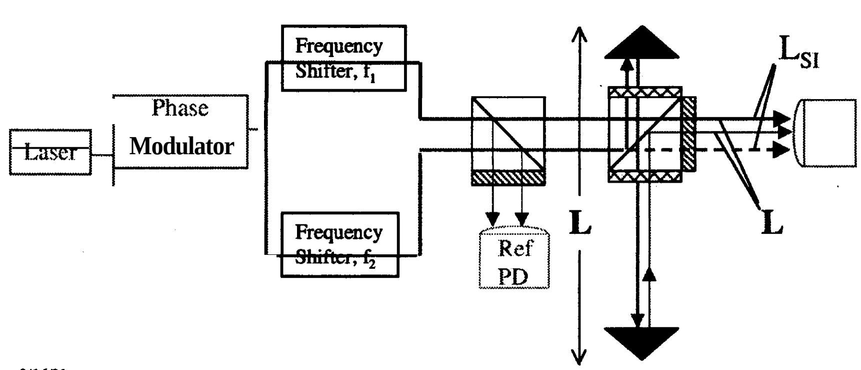
$J_1\left\{2\Delta\phi \sin\left(\Omega \frac{L}{c}\right)\right\}$ ← Magnitude of AM

RF demodulation efficiency → $\sin[\varphi_{RF}$ +



Limitations: Internal Lengths Mismatch

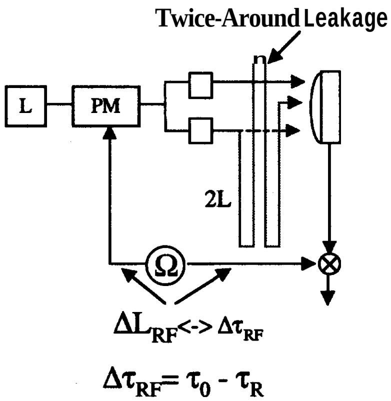


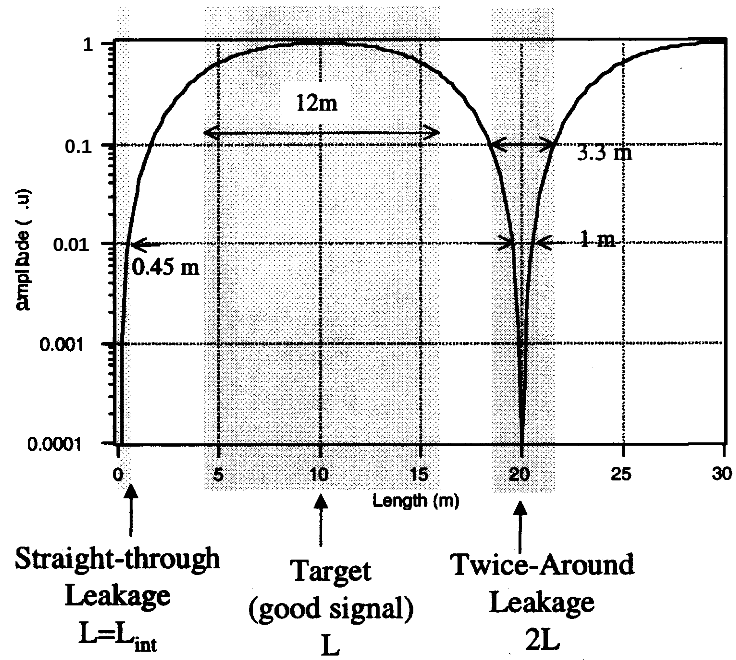


$$X = \left(\frac{L_{SI}}{L}\right)^2$$

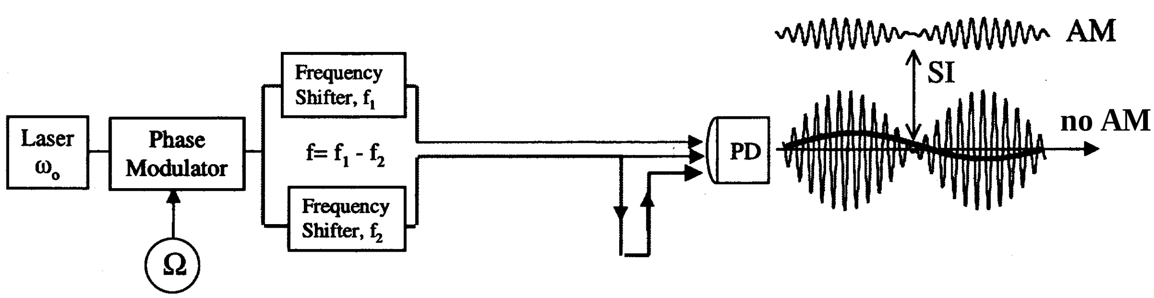
What about Twice-Around Leakage?

- How much suppression do you really need? It gets twice the loss to begin with
- If still need suppression make sure 2L hits the J1 or Cosine null





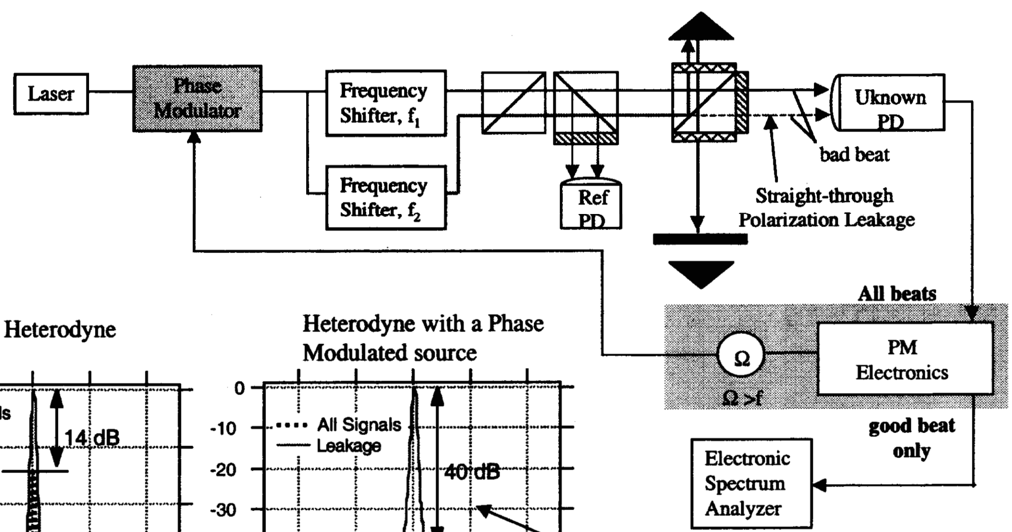
Limitations: Parasitic Amplitude Modulation

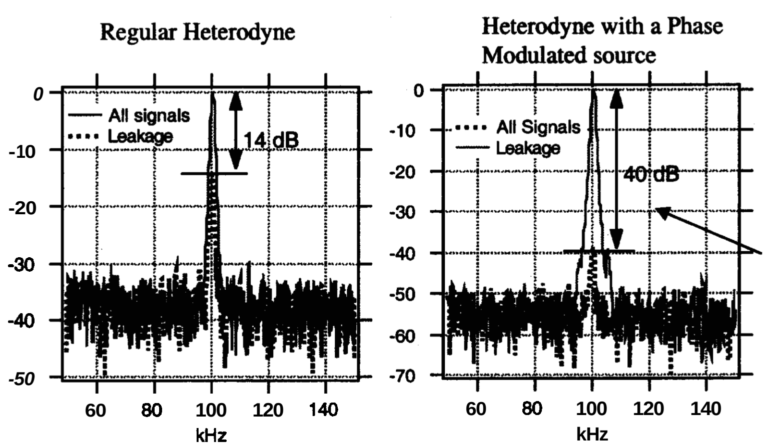


- Parasitic Amplitude Modulation: m ⟶ SI suppression: X=m
- **Amplitude Modulation results from**
  - **–Residual AM in Phase Modulator *(0.05%* spec)**
  - **–Back Reflections *into phase modulator***
  - **–**

* NEED additional 21 dB of SI suppression

SI suppression: experimental results





- 26 dB SI suppression (easy to get)
- Have done 36 dB (not a limit yet)

• **Internal Lengths Mismatch:** $X = \left(\frac{L_{SI}}{L}\right)^2$

For X=-60 dB with L=1 meter need L_{SI}=3 cm

Summary

Heterodyne Interferometer with a Phase Modulated Source:
A pre-processing method for suppression of Self-Interference in heterodyne interferometers

- Advantages:
  - Simple hardware additions with no intrusion into the measurement path
  - Heterodyne interferometer operation **is** preserved
  - No critical alignment or precise matching of parameters
- Disadvantages
  - Some knowledge of target distance is needed. Can scan modulation frequency though.
  - Twice-around leakage can be suppressed, but requires precise matching **of** phase modulation frequency with target distance. Not an issue for lossy interferometers

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Response of PM Heterodyne Interferometer

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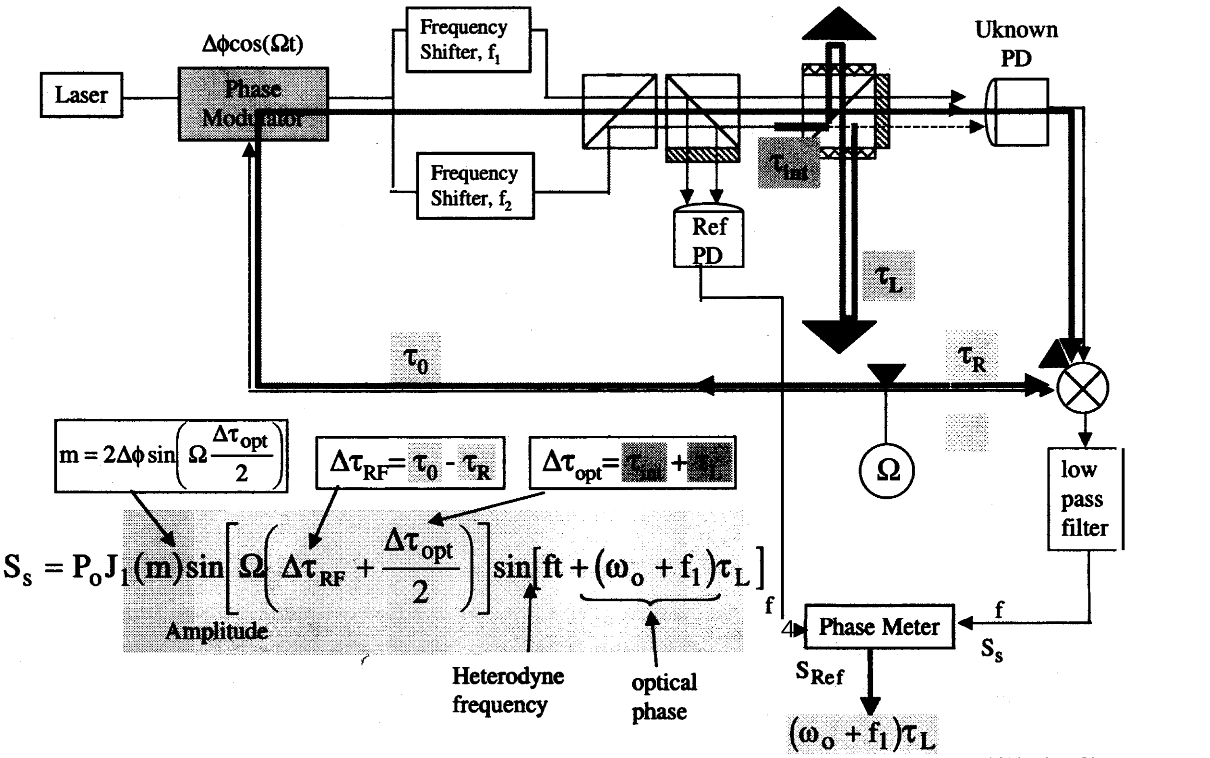

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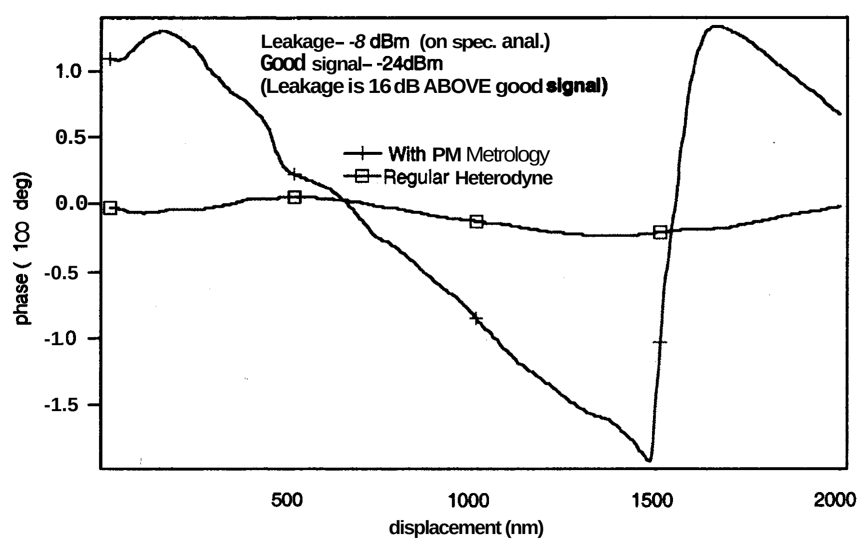
SI suppression bottom line: Measure nanometers in the presence of HUGE Self-interference

NASA

Interferometer was configured so that the self-interference signal was 16 dB (electrical power) ABOVE the "good" signal

*Regular Heterodyne: phase dominated by SI, not sensitive to target motion
•PM Heterodyne: phase dependence on target motion completely recovered

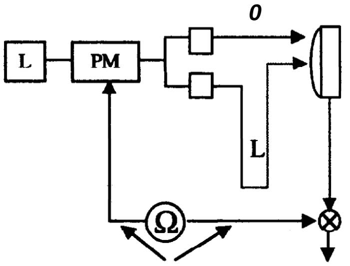


Comparison with DS3 Experimental Results

$$A = J_1\left(2\Delta\phi \sin\left(\Omega\frac{L}{c}\right)\right)\sin\left[\Omega\left(\Delta L_{RF} + L\right)\right]$$

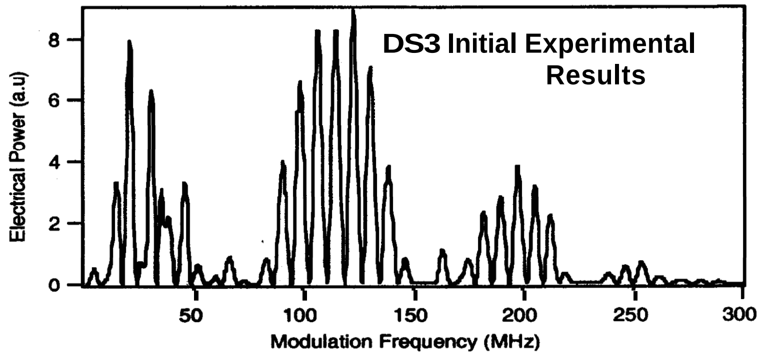
$\Delta\tau_{opt} = \cancel{\tau_{int}} + \tau_L$

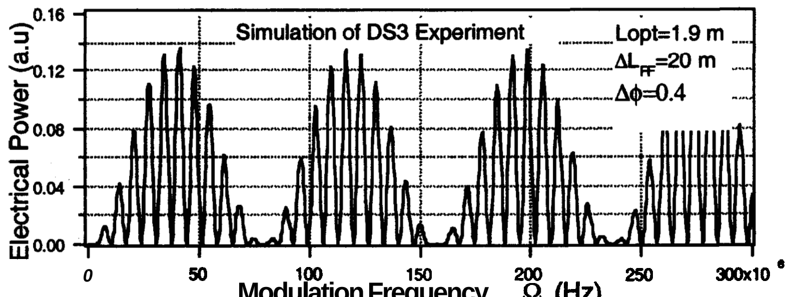
0



$\Delta L_{RF} \Leftrightarrow \Delta\tau_{RF}$

$\Delta\tau_{RF} = \tau_0 - \tau_R$





We understand experimental results

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Date

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February 16, 2001

Dr. Serge Dubovitsky

Ref: NASA Tech Brief **NPO-20740**
HETERODYNE INTERFEROMETER WITH PHASE-MODULATED CARRIER

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Deputy Manager
Commercial Technology Program

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On

HETERODYNE INTERFEROMETER WITH PHASE-MODULATED CARRIER

for February 01

NASA TECH BRIEF Vol. 25, No. 2, Item #

. from

JPL NEW TECHNOLOGY REPORT NPO-20740

Inventor(s):

Serge Dubovitsky

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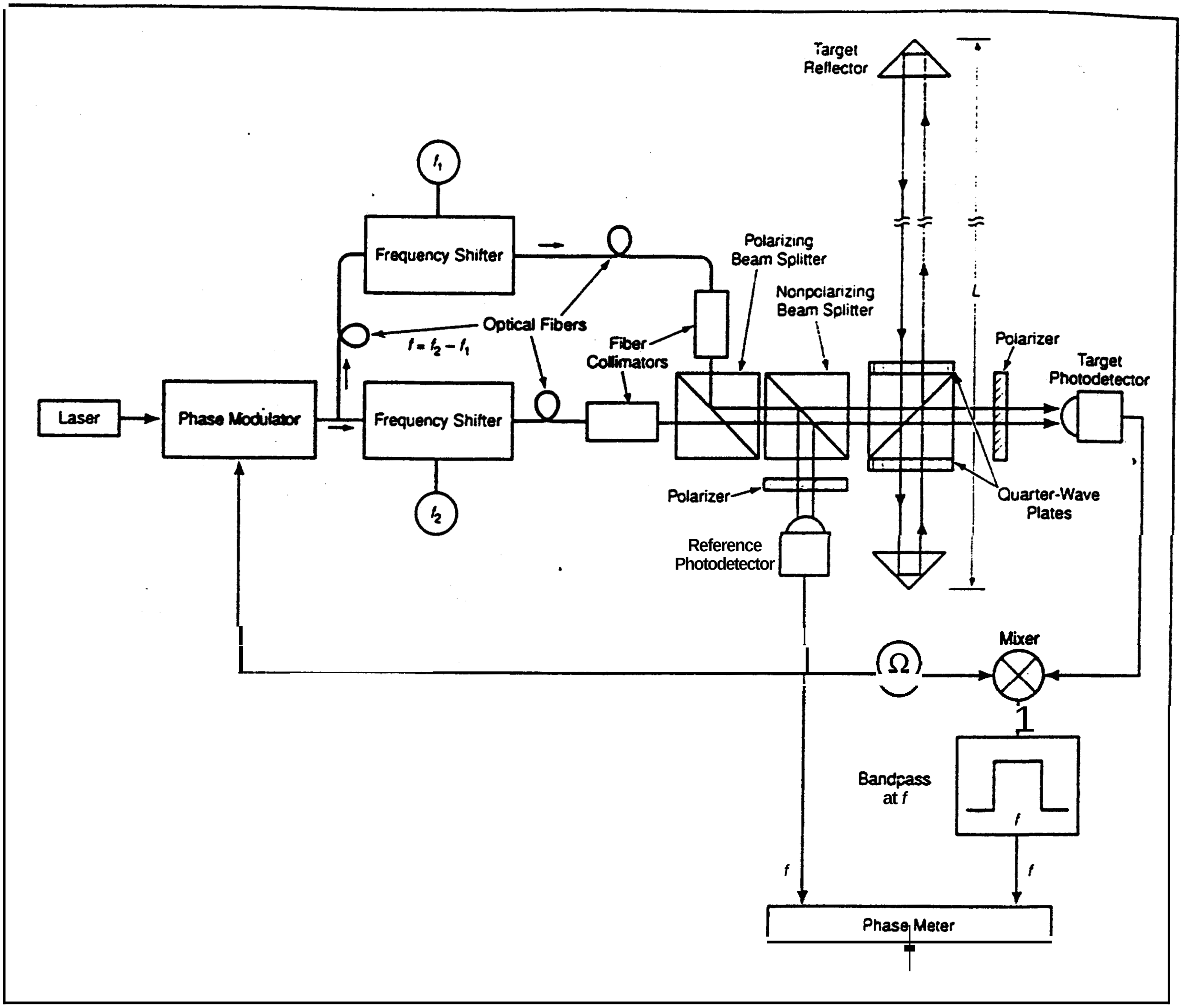
February 01

Heterodyne Interferometer With Phase-Modulated Carrier

Resolution and working distance are increased.

NASA's Jet Propulsion Laboratory, Pasadena, California



This **Heterodyne Optical Interferometer** is augmented to suppress self-interference. The augmentation consists in the addition of the shaded parts.

A heterodyne optical interferometer of a type used to measure small displacements can be augmented to suppress a phenomenon, called "self-interference," that tends to limit the achievable resolution and working distance and can even render the interferometer inoperable. The technique for suppressing self-interference can be implemented by use of commercial off-the-shelf optoelectronic and electro-optical components, and does not degrade the fundamental operation of the interferometer.

Self-interference is caused by optical scattering, imperfections in optical surfaces, and misalignment of optical components. Like many other optical interferometers, an interferometer of this type includes a target and a reference optical path. Self-interference typically manifests itself as leakage, along the reference path, of part of the optical signal power intended to propagate solely along the target path. This leakage, in turn, manifests itself as a heterodyne signal with the incorrect phase that competes against the heterodyne signal with the correct phase.

The figure schematically depicts a heterodyne interferometer configured for measuring a target path of length L. This interferometer is augmented to suppress self-interference by using phase modulation to distinguish between the leaked signal and the signal returning from the target. The following is a summary of the self-interference-suppression technique, omitting some details for the sake of brevity:

The optical carrier wave (that is, the beam coming out of the laser) is phase modulated at an angular frequency Ω before it is sent along the two paths of the interferometer. The phase modulation, by itself, is invisible to the photodetectors at the reference and target photodetectors unless it is converted, by the phase delay of one path of the interferometer relative to the other, to intensity modulation at the modulation angular frequency Ω. The self-interference signal is associated with light that does not go to the target and thus does not undergo the differential delay that would give rise to this intensity modulation.

The "good" signal is associated with the optical beam that goes to the target and thus does undergo the differential delay that gives rise to intensity modulated at angular frequency Ω. Thus, demodulation by mixing with the oscillator signal at angular frequency Ω results in discrimination against all but the "good" signal.

This work was done by Serge Dubovitsky of Caltech for **NASA's Jet Propulsion Laboratory**.

This invention is owned by NASA, and a patent application has been filed. Inquiries concerning nonexclusive or exclusive license for its commercial development should be addressed to the Patent Counsel, NASA Management Office–JPL. Refer to NPO-20740.

JPL NTR Inventor's Report

NASA CASE NO
JPL CASE NO 20749

1. Novelty

Briefly state what you think is new and different from the prior art.

Most practical interferometers used for precision sensing are based on a concept of heterodyne interferometer due to its high-precision readout afforded by the heterodyne signal processing. However, a typical optical heterodyne interferometer is limited in its resolution to a few nanometers by a parasitic leakage of optical signals called "polarization mixing" or more generally "self-interference". A number of laboratory techniques have been proposed in the past to suppress the self-interference. All of these techniques are very difficult to implement with a precision required and their implementation often introduces its own noise into the interferometer. For example, cyclic averaging by reference PO — dithering or by ramping of the frequency both degrade the inherent stability of the interferometer by destabilizing W reference arm or the carrier frequency respectively.

This invention, on the other hand, is very easy to implement, uses commercial off-the-shelf components, and affords a very high degree of self-interference suppression without degrading the fundamental operation of the interferometer

In the past phase or frequency modulation has been used in a homodyne inteferometer, e.g. H. Telle, US Patent Number 5,539,520 "Interferometer using frequency modulation of the carrier frequency". The invention described in this reports deals with a phase modulation in a much more practical heterodyne interferometer.

2. Technical Disclosure

A. Problem

State the specific problem you were trying to solve. Be as brief as possible.

Resolution of a heterodyne interferometer is limited by a parasitic leakage called "self-interference". It occurs, for example, when an optical signal instead of going to the target goes along the reference path due to optics imperfections, misalignment, and scattering. It manifests itself as a heterodyne signal with a wrong phase that competes with the heterodyne signal with the right phase. If the "good" signal is unattenuated by the optical losses, then the self-interference limits the typical interferometer resolution to about 1 nm. If the "good" signal is attenuated by the optical losses due to, for example, diffraction over long target distances, poor target reflectivity, or aperturing of the beam then parasitic signal with the wrong phase can actually dominate over the desired signal and therefore render the interferometer inoperable.

B. Solution

Briefly describe the solution.

The solution is to discriminate between the signal coming back from the target and the signal resulting from leakage and scatter. The most obvious implementation would be to dither the target in range and to demodulate the output at the dither frequency. This approach would work, but is impractical because it is difficult to implement and would degrade the inherent stability of the interferometer. Instead, the optical carrier wave is phase modulated before it is sent into the two paths of the interferometer. The phase modulation by itself is invisible to detectors at the output of the interferometer, unless it is converted to intensity modulation by the phase delay of one arm of the interferometer relative to the other. The self-interference signal, which results from the beam NOT going to the target, does not experience this differential delay and therefore does not generate an intensity modulated signal. The "good" signal results from the optical beam going to the target, experiences delay due to its propagation to and from the target and therefore does generate intensity modulation. This intensity modulation can be used discriminate and isolate the signal coming back from the target from the leakage and scatter signal. In principle, frequency, instead of phase, modulation could be used equally well, but it is much more difficult to implement and therefore is much less practical

C. Description and Explanation

Please attach a copy of the relevant technical disclosure(s) and illustration(s) describing this invention.

The invention will be described by using a particular implementation, but different implementations can used which are extensions of the present invention

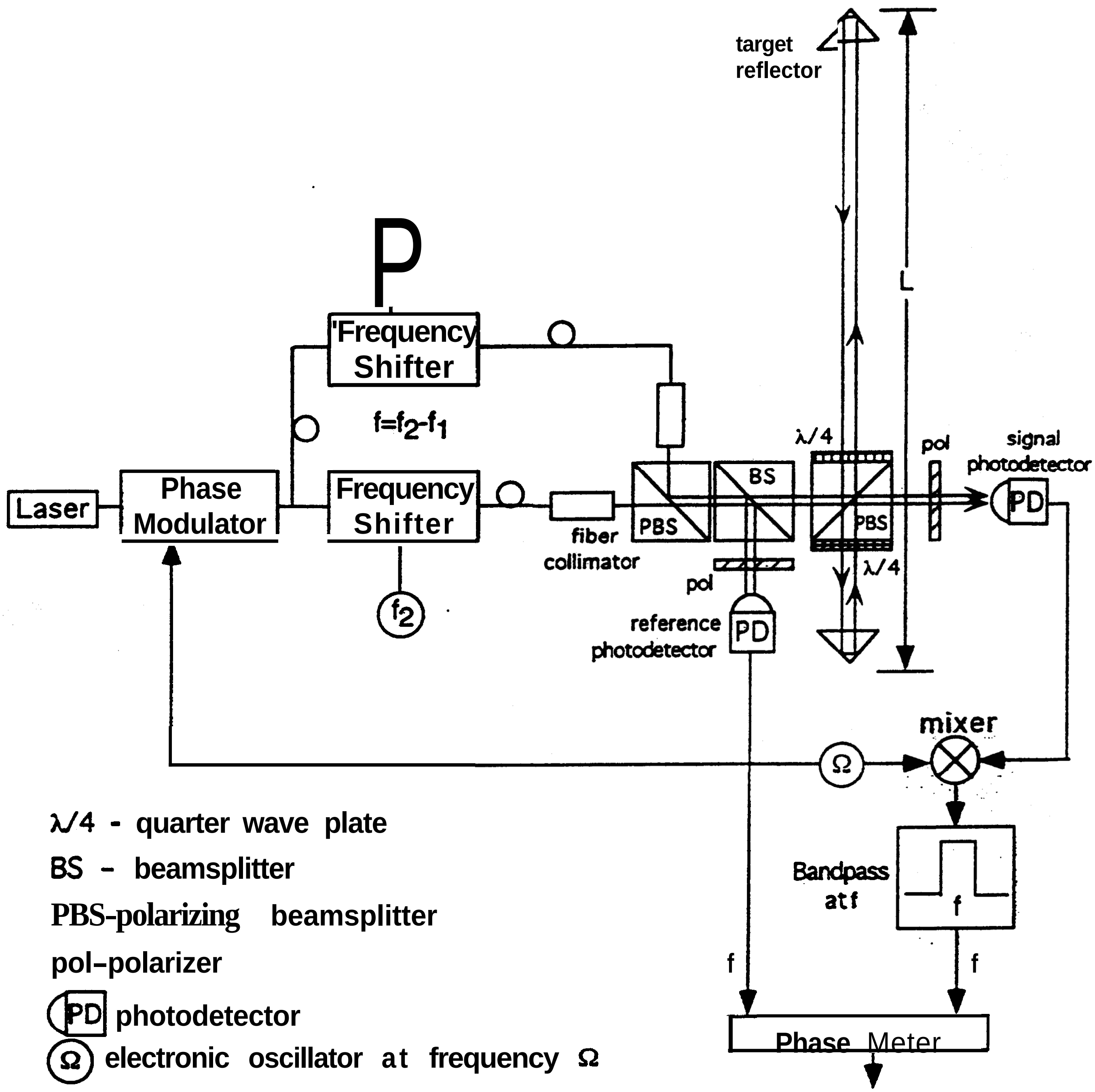


Figure 1. Heterodyne Interferometer with a Phase Modulated Source. The shaded parts are the additions to the regular heterodyne interferometer needed for phase modulation.

The schematic of the invention is shown in Figure 1. The implementation of the Heterodyne Interferometer with a Phase Modulated Source is similar to that of the regular heterodyne interferometer except for the addition of the parts shaded in the Figure. The light coming out of the laser source is phase modulated using a phase modulator (fiber-pigtailed integrated optic in this implementation) before it is split between the two legs of the heterodyne interferometer. Each leg is subsequently frequency shifted to generate a convenient heterodyne frequency, f, and the two polarizations made orthogonal to each other . The outputs of each frequency shifter are collimated and combined using a polarizing beam splitter (PBS).

Small portions of the two beams are reflected by the non-polarizing beamsplitter (BS), mixed by the polarizer, and the resulting heterodyne frequency beat detected on the reference photodetector. This beat serves as a phase reference against which the signal phase will be measured (reference Dandlicker?). The light transmitted by the beamsplitter is then redirected by the polarizing beamsplitter.
Ideally the interferometer operates as follows. The p-polarized light is transmitted and serves as an optical phase reference. The s-polarized light is reflected toward the target and is reflected back into the PBS. The polarization of the returning light is rotated by 90 degrees, because it double-passed a quarter-wave plate oriented at 45 degrees. The beam therefore is transmitted by the PBS to the reference reflector and comes back to the PBS from the other side as s-polarized light, because it was again rotated by 90 degrees by the second quarter-wave plate. At this point the s-polarized beam is recombined with the transmitted p-polarized optical reference beam. The polarized oriented at 45 degrees mixes the two orthogonally polarized beams and the interference beats are detected by the signal photodetector.
If the magnitude and frequency of the phase modulation are chosen appropriately for the target distance L, significant beats involving the phase modulation frequency (Ω) are generated at the signal photodetector. The desried heterodyne signal can be recovered by demodulating at various harmonics of Ω. In the implementation shown in Figure 1, the demodulation is performed at Ω, which downconverts the Ω-f and Q+f components into the beat at the heterodyne frequency.
The key feature of this signal processing scheme is that the magnitude of the produced heterodyne signal is proportional to $\sin(\pi\Omega L_D/c)$,

$$S \propto \sin(\pi\Omega L_D/c)$$

where c - speed of light and

L_D is the total pathlength difference between the two arms of the interferometer and consists of the pathlength due to target separation (L) and the internal pathlength mismatch of the interferemeter (L_{INT}):

$$L_D = L + L_{INT}$$

The above dependencies allow one to suppress the unwanted signals resulting from self-interference, The self-itnerference results from the non-ideal operation of the interferometer.
First, a portion of the s-polarized beam instead of being entirely reflected by the second PBS toward the target is transmitted directly into the signal photodetector. Similarly, a small portion of the beam travelling to the target may instead be scattered back by the PBS and quarter-wave surfaces. These beams would generate an self-interference beat with a wrong phase in the regular heterodyne interferometer, but in this implementation they are suppressed by the $\sin(\pi\Omega L_D/c)$. In this case, because the s-polarized beam did not travel to the target, the pathlength difference between the two legs of the interferometer is oniy the internal pathlelength difference, i.e. $L_D=L_{INT}$, which can be made to be very small. Assuming that the interferometer is optimized for operation with a target distance of L, i.e. $\sin(\pi\Omega L_D/c)$ is an appriciable number, the self-inteference signal is suppressed by a factor of L/L_{INT}.
A second source of self-interference results from the s-polarized beam travelling to the target twice. This results from polarization optics and alignment imperfections. This source of self-interference is significant only for low-loss interferometers. In high-loss interferometers it is greatly suppressed by the loss associated with an additional roundtrip to the target. The magnitude of the double-pass self-interference signal in the Heterodyne Inteferometer with a Phase Modulated Source is proportional to $\sin(2\pi\Omega L_D/c)$ and therefore can be suppressed by chosing

$$\Omega = c/(2L_D) \approx c/(2L)$$

In effect, phase modulation of the source marks the desired signal returning from the target with an intensity modulation at the frequency of phase modulation. For other signals the phase modulation of the carrier does not result in appriciable intensity modulation and they are suppressed by demodulation at the frequency of phasemodulation.

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